ELECTROSTATICALLY LEVITATED SPHERICAL 3-AXIS ACCELEROMETER

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ABSTRACT

MEMS-based electrostatically levitated spherical 3-axis accelerometer has been developed. Fabrication of the spherical MEMS device is made possible by incorporating Ball Semiconductor technology and a novel sacrificial etching process utilizing xenon difluoride gas etching through gas permeable layer. 1-millimeter diameter spherical proof mass is completely suspended without any mechanical support by closed-loop controlled electrostatic forcers. 3-axis acceleration is derived from intensity of servo feedback between capacitive position sensing and the electrostatic actuation. Noise floor is estimated as 40μG/Hz$^{1/2}$ level. After calibrating geometrical misalignment, scale factor and zero-G offset errors, linear output with minimal cross-axis error is obtained.

INTRODUCTION

Electrostatically levitated accelerometers have been utilized for micro-gravity measurement in space environment [1]. Unlike conventional pendulous accelerometers, such accelerometers don't require mechanical spring to suspend proof mass. By completely eliminating thermal noise at the mechanical suspension, extremely high sensitivity can be obtained.

Because the electrostatic force is effective only for very short range, precise narrow gap is essential for electrostatic levitation. Conventional machine-fabricated electrostatic accelerometers have been employed in very limited applications such as space missions, while MEMS-based fabrication may dramatically reduce the fabrication cost and expand potential application possibilities.

The authors have been developing spherical MEMS devices including omnidirectional clinometer and this 3-axis electrostatic accelerometer. As a material for MEMS devices, spherical shape is considered to have significant advantages because of its unique characteristics such as (i) extremely high symmetry, (ii) closed surface topology, and (iii) relatively large mass for given footprint (compared to typical surface-micromachined objects). A new sacrificial etching process technique is developed for the fabrication of the spherical MEMS devices.

OPERATION PRINCIPLE

The electromechanical structure of the spherical electrostatic accelerometer consists of a movable sphere enclosed in a shell (cage). Figure 1 shows cross-sectional view of the accelerometer. Center core (proof mass) is 1mm diameter

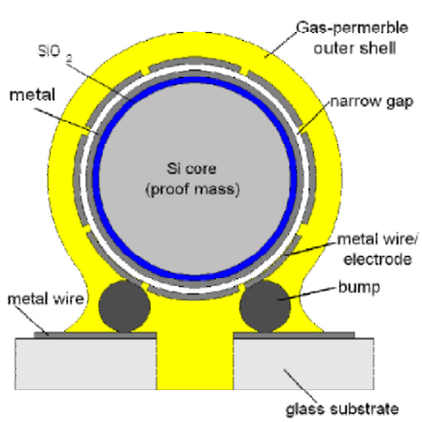


Figure 1: Cross-sectional view of accelerometer

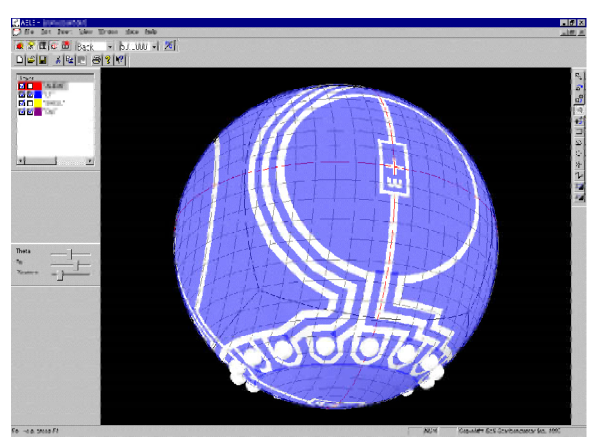
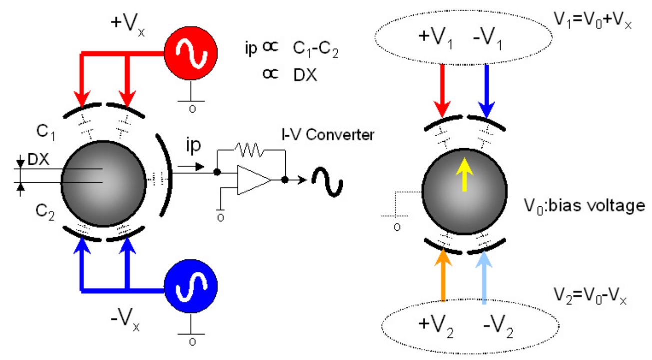


Figure 2: Accelerometer designed on spherical surface design tool

single crystal silicon weighing 1.2 milligram. Surface of the oxidized silicon sphere is covered with thin metal film. The core is surrounded by an outer shell. The core can be moved freely, as there is a narrow gap between the core and the shell. There is no wire to electrically and/or mechanically connect the core to the shell. Metal electrode pattern is placed on the inner wall of the shell. Figure 2 shows electrode pattern generated by a spherical CAD tool [2]. Six pairs of semicircular electrodes are placed at each of six orthogonal directions. Remaining blanket area is utilized as a detection electrode. All the electrodes are wired to gold bumps located at the bottom



(a)Deviation Pick-up (b)Electrostatic Actuation

Figure 3: Operation principle of spherical accelerometer

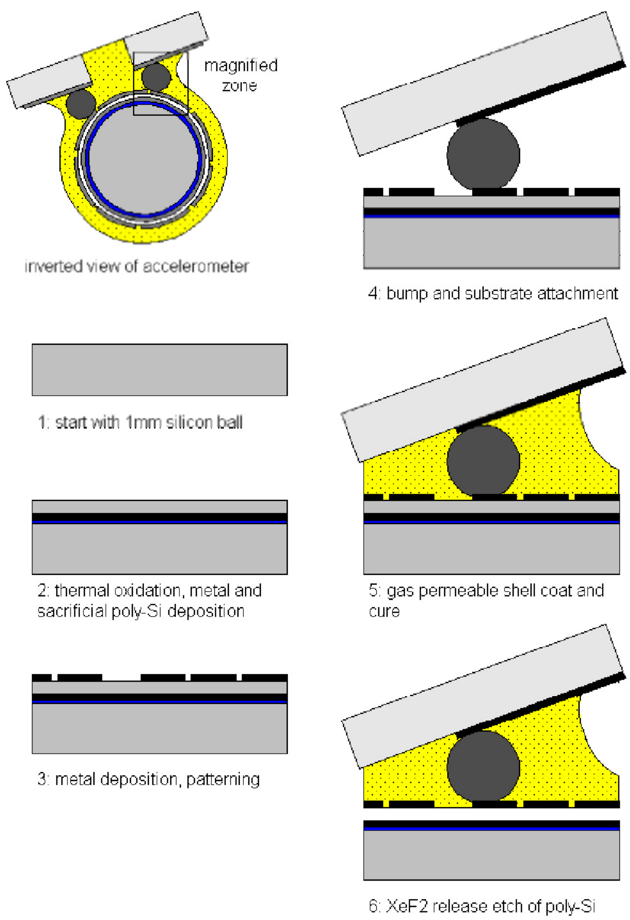


Figure 4: Fabrication process

to provide electrical interface with control circuit.

Figure 3(a) illustrates one-axis depiction of the core position (i.e. deviation) detection. A reference AC signal $+V_x$ and a phase-inverted AC signal $-V_x$ are supplied to opposing pairs of electrodes. The position of the core is derived capacitively by demodulating current i_p drawn from the blanket detection electrode with respect to the reference signal V_x. For the x, y, and z-axes, three independent reference frequencies 1, 1.25, 1.5 MHz are used so that the 3-dimensional position of the core can be measured independently.

Figure 3(b) shows one-axis schematics of electrostatic actuation. DC voltages with opposite polarity $+V_1$ and $-V_1$ are applied to a pair of semicircular electrodes on top. The electrostatic force is exerted and the core will be pulled upward. Another pair of DC voltages $+V_2$ and $-V_2$ is applied to another pair of semicircular electrodes at the bottom. Because the electrostatic force is always an attractive force regardless of voltage polarity, both the positive and negative polarities are used simultaneously so that the electrical potential at the core will be maintained neutral.

The acceleration is determined from the closed-loop feedback intensity between the capacitive position sensing and electrostatic actuation. This feedback control scheme is similar to the operation method of electrostatically levitated micro motor [3]. However, levitation of the spherical accelerometer is relatively simple because it requires only 3 degrees of freedom feedback control due to the high symmetry of the sphere.

FABRICATION

Methods employed for oxidation, thin film deposition and lithographic pattern transfer are based on Ball Semiconductor Technology descried in a previous paper [2]. A new sacrificial etching process has been developed for fabricating the precise narrow gap of the spherical accelerometer and other ball MEMS devices [4]. As shown in process flow (Figure 4), polysilicon is utilized as a sacrificial layer and gas permeable porous ceramics is chosen as the outer shell material. At the final process step, xenon difluoride (XeF_2) gas etching is implemented through the gas permeable porous shell to remove the sacrificial polysilicon layer. This method is analogous to

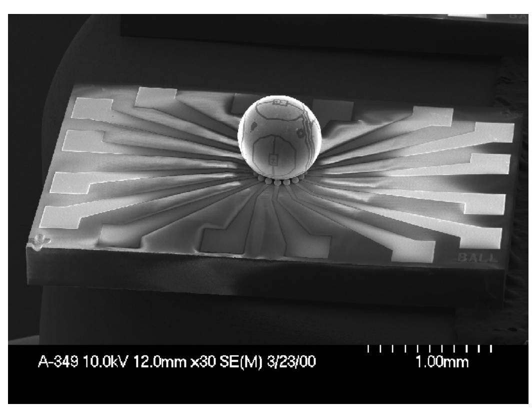


Figure 5: SEM image of accelerometer after bump attachment (Figure 4, step 4)

conventional surface micromachining process because of the way it uses sacrificial etching to create narrow gaps. This sacrificial etching method is remarkable because it provides precise narrow gap enclosure without requiring accurately aligned assembly. Utilization of this sacrificial etching approach may be useful also for other non-spherical MEMS fabrications.

SEM micrograph of the device is presented in Figure 5. Completed device is mounted on a standard 16-pin ceramic DIP package as shown in Figure 6.

EXPERIMENTAL

Fabricated devices are initially tested by open-loop mode to verify the free motion of the core. The devices are then evaluated in a 3-axis closed loop levitation mode. All tests are carried out in atmospheric pressure environment.

In the initial open-loop test, the devices are mounted on a tumble stage and it is slowly inclined back and forth between –180~+180° for several times. As shown in Figure 7, the motion of the core is confirmed although some hysteresis behavior is observed. The hysteresis seems to be caused by tribological reasons. Although the hysteresis may limit its sensitivity, this open-loop operated device may be utilized as omnidirectional clinometer with simple peripheral circuit [5].

After confirming the free core motion, the 3-axis closed loop levitation is implemented. The control circuit is powered

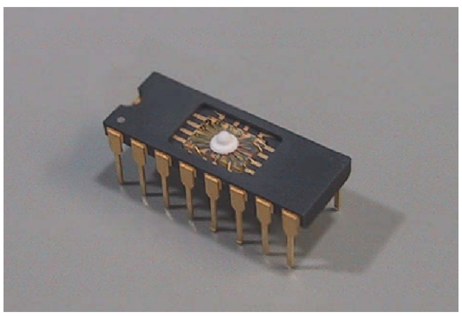


Figure 6: Spherical accelerometer mounted on 16-pin ceramic DIP package

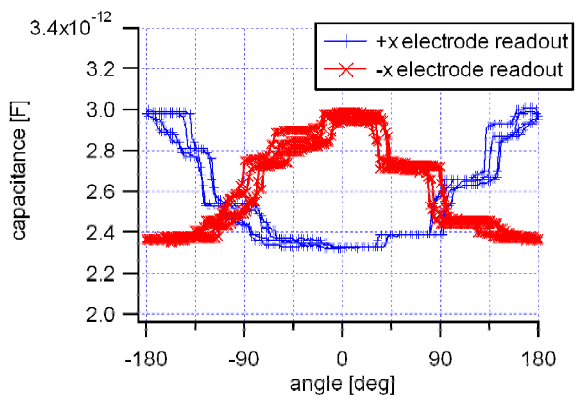


Figure 7: Open-loop operated test result

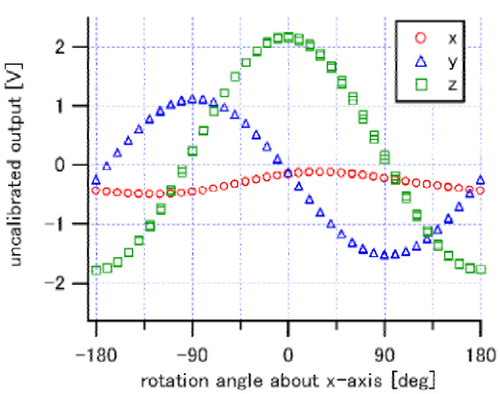


Figure 8: Uncalibrated accelerometer output

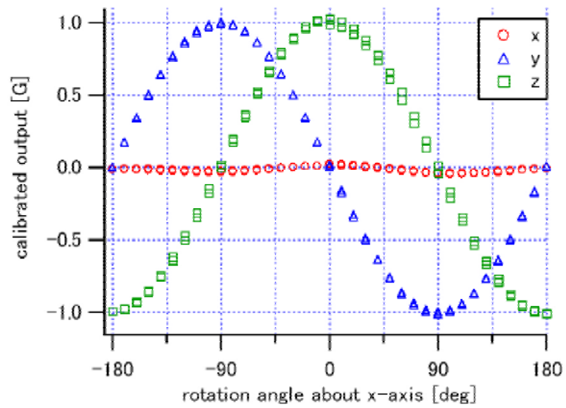


Fig. 9(a)

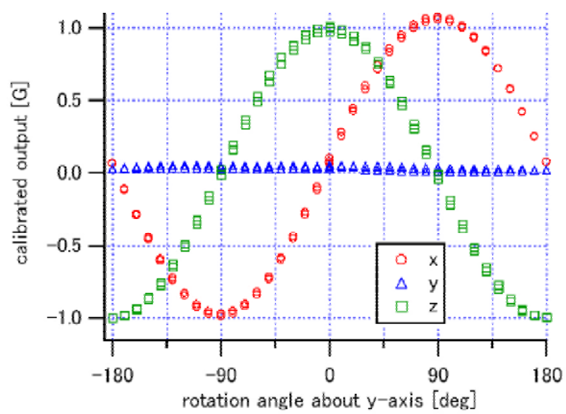


Fig. 9(b)

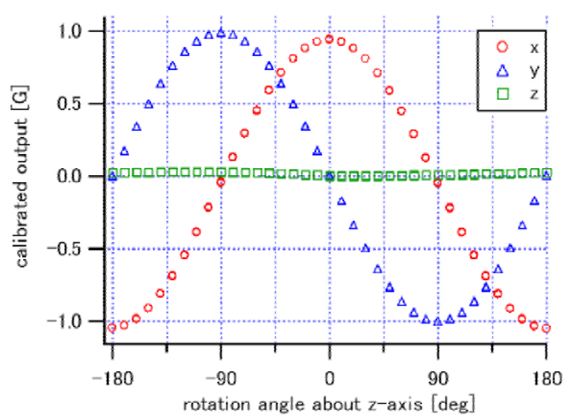


Fig. 9(c)

Figure 9: Calibrated accelerometer characteristics measured on tumble stage

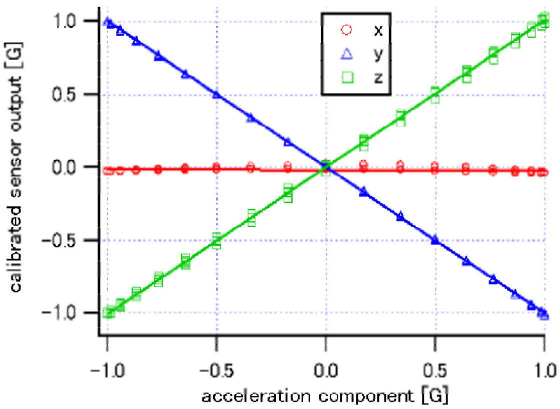


Figure 10: Accelerometer linearity

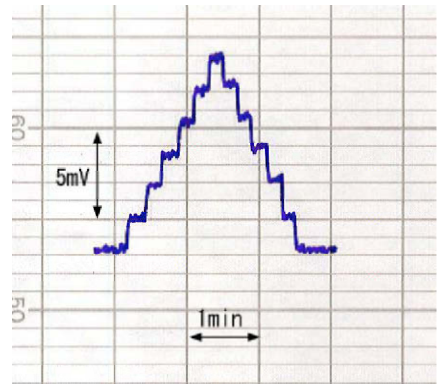


Figure 11: Accelerometer resolution test (each increment is equivalent to 1.45mG)

by either ±15 or ±30 V DC supply. Higher voltage circuit is necessary for the samples made with larger gaps and/or for increase the acceleration range. For the samples made with 2µm polysilicon thickness (i.e. 4µm maximum gap width at start-up), ±15V circuit is appropriate for levitating the proof mass up to ±2G load. Results in this paper are obtained with 4µm sacrificial layer thickness (i.e. 8µm maximum gap width at start-up) units and ±30 V DC peripheral circuit.

Figure 8 shows uncalibrated acceleration output measured on the tumble stage rotated about x-axis. Before calibration, significant zero-G offset and scale factor error exists. Moreover, the x-axis plot appears to be a sinusoidal curve instead of expected flat line even though the applied x-axis acceleration component is always zero throughout this measurement. This behavior is considered to be an artifact caused by imperfect symmetry of the electrode pattern. As shown in the figure 2, the electrode pattern is not completely symmetrical since bumping pads and wires are placed on the same metal layer. However, this geometrical misalignment factor can be compensated by a linear transformation, which converts the effective closed-loop control axes to the true orthogonal axes by a matrix conversion. The zero-G offset and the scale factor can be calibrated simultaneously in the same numerical linear transformation. Figure 9(a, b and c) shows the calibrated sensor output of the spherical accelerometer. After the calibration, cross-axis sensitivity is minimized as shown in Figure 10.

Resolution of the accelerometer is demonstrated in Figure 11. The device mounted on the tumble stage is intermittently tilted by 5' step (equivalent to 1.45mG increment) for six steps forward and backward. The sensor output is plotted on a pen recorder with a 1Hz filter. Presently noise floor is estimated at 40µG/Hz$^{1/2}$ level, and it is expected to be improved by refining the peripheral servo circuit.

CONCLUSION

MEMS-based electrostatic spherical 3-axis accelerometer has been developed. A novel sacrificial etching process scheme has been successfully utilized for the fabrication. The proof mass of the fabricated accelerometer is fully levitated by 3-axis closed-loop control. Linear output with minimal cross-axis sensitivity has been demonstrated.

ACKNOWLEDGMENT

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